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Quasi-static Energy Absorption Performance of Conical Coir Fibre Reinforced Polyester Composites

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ABSTRACT

The energy absorption capability of a composite material is critical to developing improved human safety in automotive compartment during vehicular collisions. Experimental investigation was conducted to study the crushing effect of conical coir fibre reinforced composites under quasi-static loading. Three semi-vertex angles and fibre loadings were selected in fabricating the conical composites. Load/displacement curves and deformation histories of cones under compressive loadings were presented and discussed. The results showed that both semi-vertex angles and fibre loadings played an important role in determining the energy absorption capability and controlling factor in changing the failure modes. It is important that an increase in vertex angle worked as triggering mechanisms providing a stable progressive collapse resulted higher energy absorption performance.

Keywords: Energy absorption, natural fibre, composite, stable progressive collapse, failure modes.

ABSTRAK

Kebolehan penyerapan tenaga oleh bahan komposit adalah sangat penting untuk membangunkan penambahbaikan terhadap keselamatan manusia di dalam struktur automotif semasa perlanggaran. Kajian secara eksperimen telah dijalankan untuk mengkaji kesan kerenyutan komposit yang diperkuat serat kelapa yang berbentuk kon bila dikenakan daya mampatan statik. Tiga jenis sudut separuh condong dan kandungan serat telah dipilih untuk pembikinan kon komposit. Lengkung beban/anjakan dan jujukan ubahbentuk kon komposit dibentangkan dan dibincangkan. Keputusan menunjukkan yang kedua-dua sudut separuh condong dan kandungan serat memainkan peranan yang penting dalam menentukan kebolehan penyerapan tenaga dan faktor pengawalan dalam mengubah mod kegagalan. Adalah penting untuk dinyatakan yang peningkatan sudut condong berfungsi sebagai mekanisma pemancu yang menyediakan keruntuhan komposit secara stabil dan berterusan dan seterusnya menghasilkan prestasi penyerapan tenaga yang tinggi.

Kata kunci: Penyerapan tenaga, serat semulajadi, komposit, keruntuhan stabil dan berterusan, mod kegagalan.

INTRODUCTION

Research into the use of structural components for energy management is not new. As a result, the energy absorbing characteristics of metals are fairly well understood. Most of the research on the energy absorption of metals has concentrated on thin walled cylinders of simple cross sections. However, as early as the late 1970's, attempts at understanding the energy absorbing capabilities and crushing mechanisms of fibre-reinforced polymer composites have been made (Thornton 1979). Most fibre reinforced composites absorb energy through a combination of fracture and friction (Thornton 1990), whereas metals absorb energy through plastic deformation (Thornton 1990; Hull 1982; Johnson & Reid 1991).

In order for either a metal or a composite to absorb energy efficiently, stable progressive crushing must occur. A stable progressive crush is characterized by localized failure that begins at one end of the specimen and progresses through the specimen without significant damage past this crush front. To ensure stable crushing, in both metals and fibre-reinforced composites, a crush initiator, which creates a local stress concentration, is used. If stable crushing is not established, the specimen will then usually fail catastrophically. During catastrophic failure the peak load is very high and drops off quickly, so the average load is low. This behaviour was also called "buckling process". Catastrophic failures are clearly not acceptable for energy management. When studying energy absorption there are many important variables. These include material; manufacturing method; microstructure; geometry of specimen, including any crush initiator used; and rate of crush. An important parameter when studying energy absorption, and one often used in the automotive industry, is the energy absorbed per unit mass of crushed material. This is often called the specific energy absorption (SEA). The SEA provides a measure of energy absorption efficiency of a structural component but says nothing about the efficiency of the structure with regards to other areas, such as resisting buckling, damping vibration, or its ease of manufacture. It is one of several parameters that must be considered in automotive design.

Hull (1982) classified the types of progressive crush failure into fibre splaying and bending, fibre splaying and axial tearing, and micro-fragmentation. The fibre splaying and bending mode was similar to the lamina bending mode of Farley and Jones (1992). The fibre splaying and axial tearing mode was characterized by some layers bending inward and some layers bending outward, and the layers tearing into petal-like sections called "fronds". With both forms of fibre splaying, a wedge of debris was present at the crush "front", between the inward and outward splaying fibres. When the composite was reduced to powder and very small fragments, Hull called this micro-fragmentation. Hull (1991) also classified three modes of failure for square-ended brittle-material tubes. These three modes were Euler buckling, which was easily avoided; shell buckling and progressive folding; and brittle fracture. The brittle fracture mode was then further categorized into catastrophic failure and progressive crushing, and progressive crushing was further categorized into splaying and fragmentation. "Splaying" covered both of the types of failure described above (Hull 1982). Fragmentation was characterized by crushing and then breaking off of small pieces both inside and outside of the tube.

Plant fibres are currently only used in the interior of passenger cars and truck cabins. Besides their use in trim parts such as door panels or cabin linings, plant fibres are used extensively for thermo-acoustic insulation. Such insulating materials, mainly based on cotton fibres recycled from textiles, have relatively high fibre contents of more than 80% by weight. Trim parts in Brazilian trucks, made of a mixture of jute coffee bag waste and polypropylene bags show that recycling sometimes can lead to advanced applications. Another well established field of application is the use of coconut fibres bonded to natural latex for seat cushions. For this application the ability of plant fibres to absorb large amounts of humidity leads to an increased comfort that cannot be obtained with synthetic materials. Aside from this kind of developments, fundamentally new applications have not been realized in recent years (Lim et al. 2003; Torres and Cubillas 2005).

A comprehensive experimental investigation of the quasi-static axial crushing of natural fibre/polyester composite solid cones between flat flattens has been carried out (Mahdi at al. 2004). The composite solid cones were fabricated from two types of natural fibre namely oil palm fibre

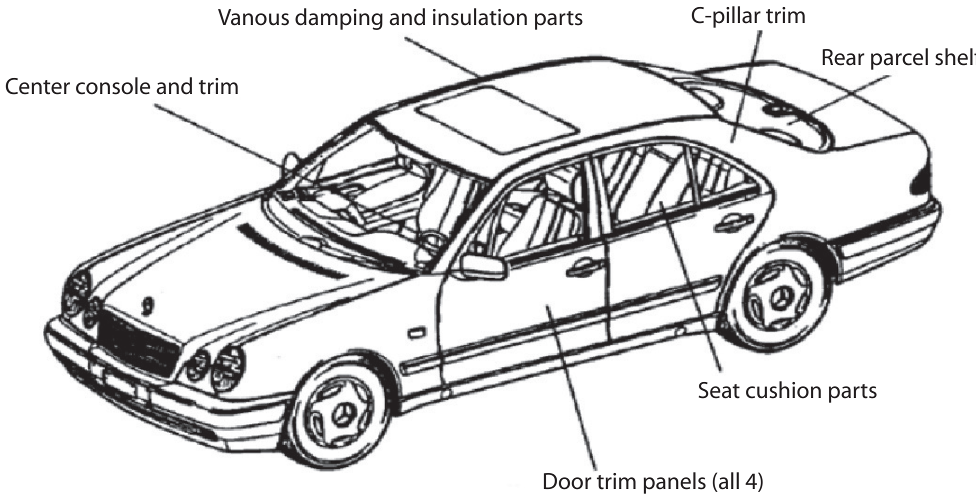


FIGURE 1. Natural fibre reinforced composite application in automotives.

and coir fibre and different vortex angles carried from 0^0 to 60^0. In their study found that reinforcement type greatly affects the crashworthiness parameters for the natural fibre solid composites and an increase in cone vertex angles results in non-flatter load-deformation curves.

Price and Hull (1987) investigated the energy absorption capability of hollow glass polyester truncated cones, or frusta, under axial compression. It was found that frusta with relative densities above approximately 0.2 failed by a progressive crushing mechanism with specific energy absorptions which in some cases exceeded those of axisymmetric tubes made from the same material. Values of up to 120 kJ/kg were recorded. The principal factors affecting energy absorption were found to be wall thickness, section diameter and semi-apical angle, although the relationship between these parameters was complex.

Mamalis *et al*. (1991) and Mamalis *et al*. (1992) provided more specific information on the effect of semi-apical angle on the energy absorption capability of frusta. In general, specific energy absorption was found to fall with increasing semi-apical angle. Furthermore, a critical angle for the transition between stable and unstable collapse was identified as lying between 15^o and 20^o. Both Hull (1991) and Mamalis *et al*. (1991) make the important observation that, contrary to what is commonly experienced with the failure of circular FRP tubes, conical specimens do not require a collapse trigger mechanism to avoid initial catastrophic failure. Fracture is automatically initiated at the narrow end of the frustum in the region of highest stress.

Basically, unidirectional fibres can support the compressive load which is applied in the longitudinal direction of the fibres. Crushing element under compressive load, therefore require unidirectional fibres. Usually, however, cracks within the fibre bundles occur easily in this material system. Hull (1991) suggested the importance of the ratio of axial fibres to hoop fibres because crack in the unidirectional fibres are prevented by hoop fibres which can apply a radial compressive stress. The specific energy absorption (SEA) value is calculated from the mean crushing load, P the area of cross section, A and the density of the material, ρ as follows;

$$E_S = \frac{p}{A\rho} \tag{1}$$

The units of E_s which express the crushing performance, therefore in kJ/kg. E_s values for various materials, including metallic materials are summarized in Table 1.

In this work, coconut coir was used to reinforce the polyester resin. Quasi-static axial compressive tests were conducted on the conical composite with different vertex angles and fibre volume fractions. The specific energy absorption

TABLE 1. SEA values of various materials (Hamada et al. 2000)

Reinforcement	Matrix	E_s
Glass fibre	Epoxy	53.7
Aramid fibre	Epoxy	57.9
Carbon fibre	Epoxy	82.1
Steel		33.7
Aluminium		66.9

for each cone conditions were evaluated and discussed by correlating with both vertex angles and fibre loadings. Then, collapse mechanisms were observed and discussed.

EXPERIMENTAL METHOD

Coconut coir fibres were obtained locally. They had random orientations and the lengths of fibre were in the average length about 102mm with maximum diameter less than 0.5mm. Steel mould was prepared with different semi-vertex angles 5, 10 and 15^0. A 20mm space between two mould surfaces was prepared to fill the coir fibres. 20, 30 and 40% of volume fraction of fibre occupied into this space prior to pour polyester resin. Careful consideration was emphasized in this stage in order to avoid any pore formation, to do this transparent outer mould was used to monitor the progressive filling polyester into the mould. The inside surfaces of both mould were covered by a layer of wax in order to make it easier to extract the cone from the mould. The fabrication process was conducted in controlled environment of 25^0C, 50% relative humidity and after 24 hours the hardened composite was removed from the mould, this is because the composite would have enough time to shrink and fully hardened. Table 2 summarized the parameter involved in fabricating the conical specimens.

Purification processes were conducted on as-received natural fibres in order to modify the surfaces of natural fibre and therefore enhancing the quality of bonding with polymeric matrix. The fibres were soaked into 5% sodium hydroxide solution for 24 hrs to remove any contaminated or unwanted debris/layer from fibres surface and rinsed with distilled water 3 times. The fibres were dried in furnace environment at 800ºc for 24 hrs in order to remove moisture content.

Quasi-static compression tests were conducted on these conical composite with constant cross-head displacement of 1.5mm/min using a universal testing machine (UTM). The specimen was placed between the two flat platens and the bottom surface was fixed in all degrees of orientation. The specimens were aligned centrally so that the compressive load distributed uniformly. During the test, the collapsible mechanisms were monitored in order to analyze the behaviour of deformation. The bottom platen was fitted with a load cell from which the load signal was taken directly to the computer. For each test, the crush load was plotted on the *Y*-axis and the crosshead displacement on the *X*-axis.

The total work done (*W*) during the axial crushing of the cones are equal to the area under the load/displacement curve and is evaluated as:

$$W = \int P ds \tag{2.0}$$

where, *P* is the force acting on the composite cones. Therefore, the specific energy absorption per unit mass, E_s is recognized as:

$$E = \frac{W}{m} \tag{3.0}$$

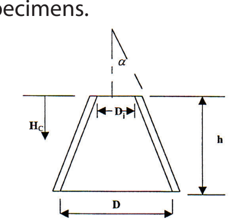
where, *m* is the crushed mass of the composite.

RESULTS AND DISCUSSION

The effect of fibre volume fraction on the energy absorption has not been extensively studied. A possible explanation for the statement is that as the fibre volume fraction increases, the volume of the matrix between the fibre decreases. This

TABLE 2. The parameters involved in fabricating the conical specimens.

Degree, α	h(mm)	D_i (mm)		t(mm)
5	110	96	118	12
10	110	92	135	12
20	110	93	174	12



cause an increase in the matrix density. This further leads to a decrease in the interlaminar strength of the composite. As interlaminar strength decreases, interlaminar cracks form at lower loads, resulting in a reduction in the energy absorption capability (George *et al*. 2002). Therefore, the changes in the energy absorption trends with fibre content and vertex angle are determined by the crushing response of the composite material.

5^0 semi-vertex angle cones

The load/displacement curves of conical coir fibre reinforced composites are shown in Figure 2. This figure shows a typical crushing deformation of the composite tube or cone subjected to quasi-static compressive load. Linearity is evident during the precrush- stage, where axisymmetric buckling initiates the failure at the top end of the specimen as shown in Figure 3(c). In this stage the cone resistance reaches its first and highest peak (range between 5 – 10kN) and at a deformation of 40mm. Subsequently the tube load-carrying capacity decreases slightly as the crushing process progresses. It is seen that the progressive folding buckling is dominating the post crush stage. The tube resistance reaches its lowest magnitude of about 5kN for 20% fiber loading composite at 40mm deformation (see Figure 2). A rapid rise of the load was observed and found to be occurred at deformation of 60mm as illustrated clearly in Figure 2.

A longer initial displacement is due to higher compressive loading required to stress the composite because the 5^0 semi-vertex angle did not provide a sufficient triggering mechanism which contributed to stable progressive collapse of composite walls. Shorter stable progressive collapses are observed for 20 and 30% fibre loading composites indicating that catastrophic failure has occurred during progressive collapse just after linear deformation. This feature contributes to low energy absorption capability.

After the 60mm cone deformation, the load increased gradually indicating the conical deformation has entered the densification region due to composite wall bent inward at the top end. Crushing history is depicted in Figure 3. As expected the first folding started at the top end of the cone and progressively collapse down through localized buckling of the composite wall. Figure 3d and 3e revealed clearly that after cone experiencing linear deformation, global buckling occurs during the crushing progress of the composite wall contributing to lower energy absorption capability.

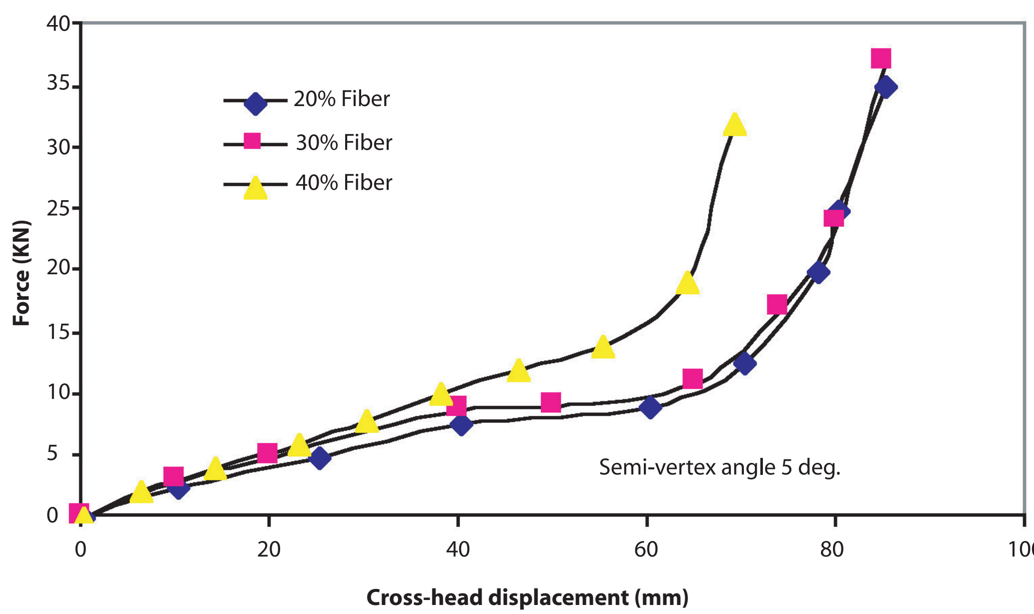


FIGURE 2. Force-displacement curves of conical composite with semi-vertex angle 5^0 with different fibre volume fractions.

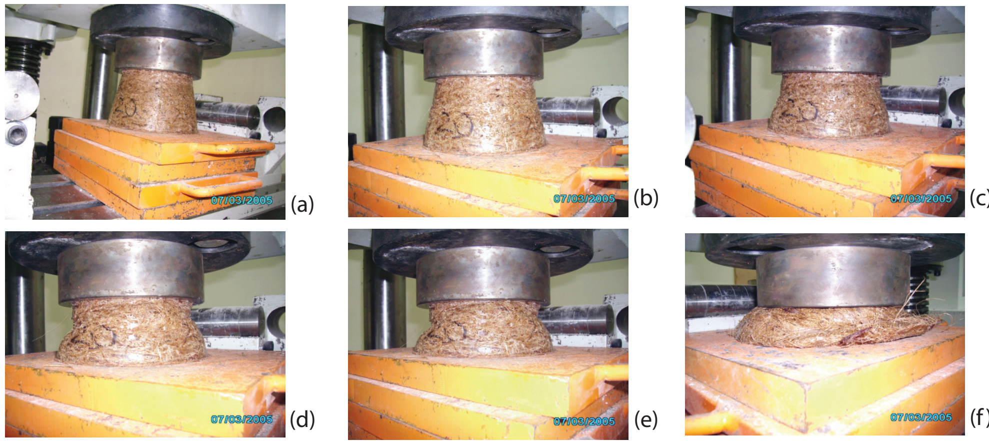


FIGURE 3. The sequence of cone deformations under axial compressive loading (vertex angle 5^0 and 20% fibre volume fraction).

10^0 semi-vertex angle cones

A typical force/displacement curve under quasi-static loading is shown in Figure 4. Composite contained 40% fibre loading produces higher composite resistance to deformation compare to other composites. Initially, the load increases linearly with increasing displacement without showing any initial crushing failure load clearly where the load exhibit constant increment. After the 30mm displacement, the 20 and 30% fibre loading composites experience no curve fluctuation with narrow peaks and troughs as the displacement increases as typically observed for quasi-statically compressed composite tubes or cones [Hull, 1991]. The composites continue to collapse in stable manner without increasing the load after leaving the linearly deformed region. This behaviour was clearly seen for 20 and 30% fibre loading composites. Longer distance of this region better energy absorbed capability. Figure 5 shows the history of composite deformation under quasi-static loading. A different failure mechanism is observed for conical composite fabricated using 10^0 semi vertex angle. When the composite is compressed, the conical wall composite at the bottom edge of the cone expanded and splayed outward. In this stage, the axial load rises in a steady rate and micro-fragmentation is observed at that location. As the load rise again, the wall continued to expand outward and cracked. Figure 5f depicted the final crushing mode of the conical composite which containing 20% fibre loading. This failure mechanisms results in higher energy absorption capability compared to previous types of composites.

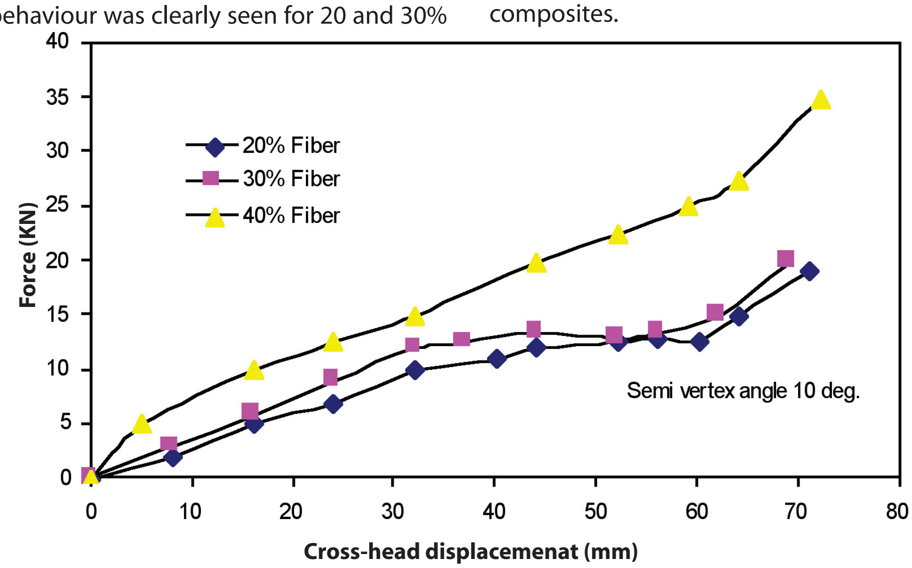


FIGURE 4. Force-displacement curves of conical composite with semi-vertex angle 10^0 with different fibre volume fractions.

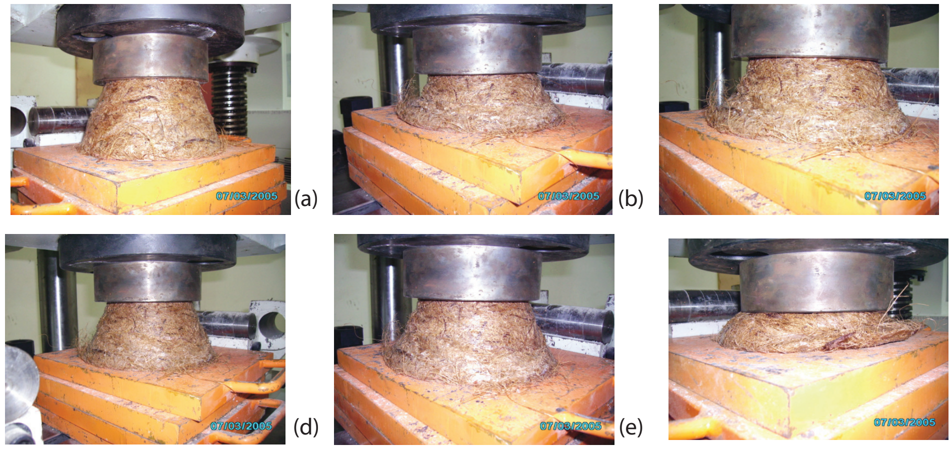


FIGURE 5. The sequence of cone deformations under axial compressive loading (vertex angle 10^0 and 40% fibre volume fraction).

20^0 semi-vertex angle cones

The load/displacement curves for cone fabricated using 20^0 semi-vertex angle are shown in Figure 6. These curves show no significant load fluctuations and load increased linearly in short range less than 10mm before entering post-crushing regions. The crushing load for 40% fibre loading composite is higher than other types of composites. These cones started showing higher compressed load at earlier stage less than 60mm compared to 5 and 10^0 semi-vertex angles. Conical composites result the highest energy absorption capability. The 20 and 30% fibre loading composites generate typical force/displacement curve showing longer stable progressive displacement after linear compressive displacement. A longer post-crushing displacement is responsible to provide high energy absorption performance through progressive collapse of composite walls at almost constant compressive loading. The deformation history for 20^0 semi-vertex angle composite is similar to Figure 5. The first collapse occurred at the bottom edge contact with static flat platen. Larger contact area is induced as load increases where the composite wall bent outward through matrix cracking and splayed on the flat platen. The interaction between these two materials increased the frictional force and preventing a sudden drop of compressive loading that contributed to catastrophic failure.

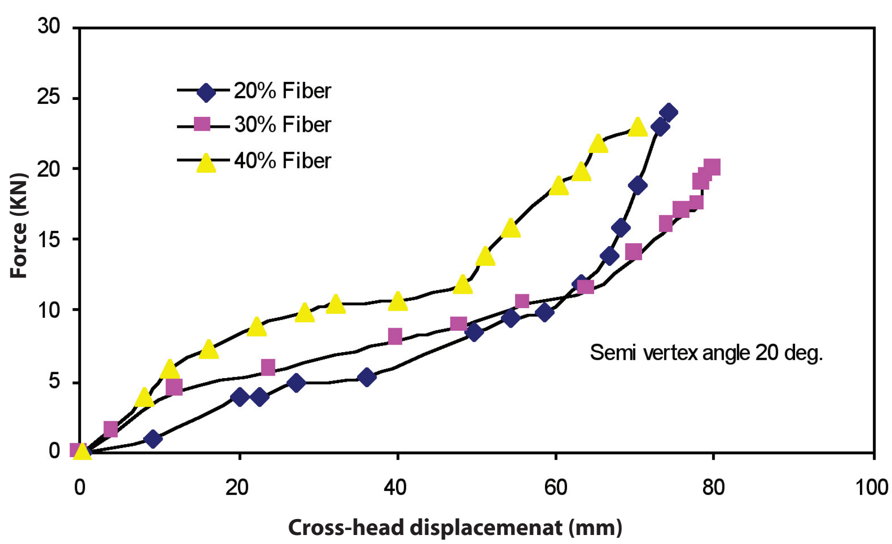


FIGURE 6. Force-displacement curves of conical composite with semi-vertex angle 20^0 with different fiber volume fractions.

Specific energy absorption

The energy absorbed during the crushing process is the area under the load/displacement curve. This area depends on the amount of the specimen crushed and the material mass density. The values of the specific energy absorption were calculated by smoothing out the serrations to obtain an average value of the load at each stage of crushing. The mean or average crush loads were multiplied with crush distance in order to obtain energy absorption performances. Hence, the specific energy absorption is given by equation (1). In the case of conical composites, the specific energy absorption change with crush distance. Therefore, at any position of crush, cross-sectional area is given by:

$$A = \pi t\,(2h_c \tan\alpha + t + D_i) \qquad (4.0)$$

The specific energy absorption of conical coir fibre reinforced composites is presented in Figure 7. The crushing process of the cone depends upon the mechanical properties of the fibre and matrix, fibre volume fraction, laminate stacking sequence, fibre architecture, and geometry of the tube. The deformation history indicates that the localized buckling on the composite wall has occurred for composite fabricated with semi-vertex angle 10 and 20^0 and it is more efficient for energy absorbing design. One of the interesting observations that have been found is that for the higher energy absorption performance, at the bottom edge of the cone, the cone wall bent outward around the circumference of the cone. This mechanism has contributed to increase the performance of the energy absorptions and preventing the composite wall from global buckling and therefore producing the progressive stable collapse of the conical composites.

It is seen that vertex angles play an important role to strengthen the composite resistance to deformation under axial compressive loading. This can be observed from results in Figure 7. The 5^0 semi-vertex angle composites result in the lowest energy absorption performance. This is because global buckling is observed just after the linear deformation. This catastrophic failure produces lower a energy absorption capability.

Work by Berry and Hull (1984) on SMC showed that an increase in fibre volume fraction from 13 to 18% gave an increase in specific energy from 39 to 54kJ/kg. While Wess *et al.* (1988) varied the fibre volume fraction between 10 and 60% in glass/epoxy composite material compressed quasi-statically and they found that the specific energy absorption improves with increasing fibre volume fraction and it reaches saturation at fibre content above 50%. As the fibre volume fraction increases, then generally the material density increases by assuming fibre density is always higher than matrix resin density. If the specific energy is to increase, then the crush load must increase by an amount that exceeds the increase in material density.

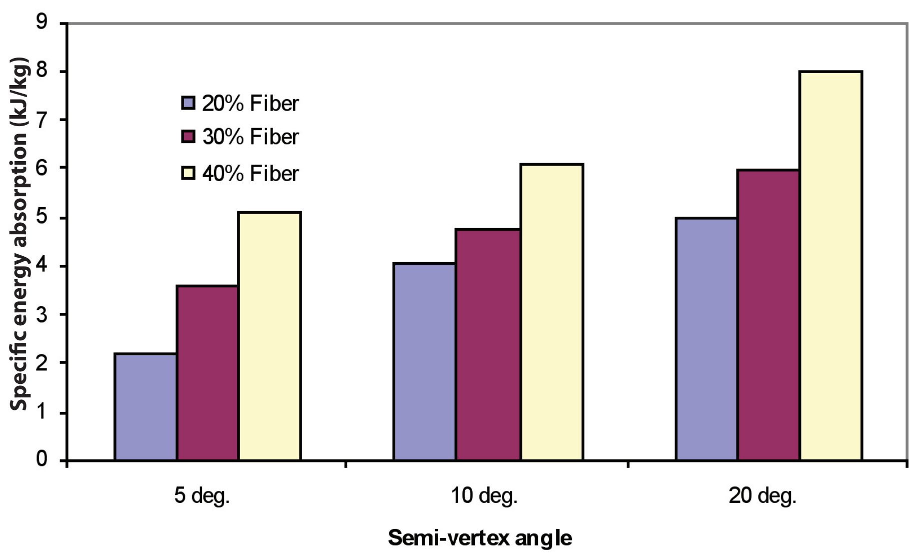


FIGURE 7. Specific energy absorption of conical composites.

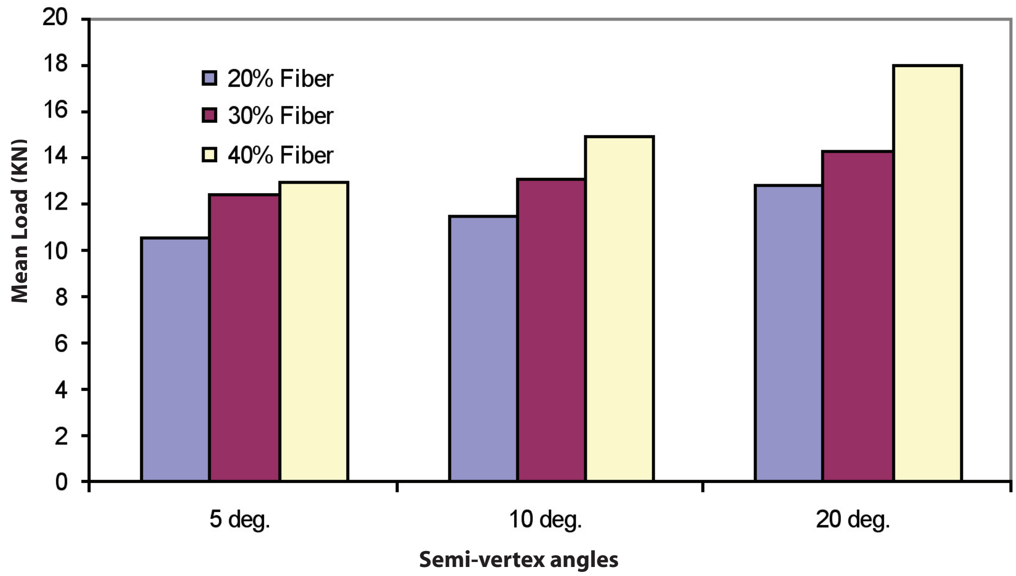


FIGURE 8. Effect of vertex angle on mean load under axial crushing loads.

The results of the relationship between vertex angle and mean load are presented in Figure 8. Mean load is obtained by averaging the crushing loads over the crush displacement through the stable load/displacement curves. It is evident that an increase in cone vertex angle from 0 to 20^0 increases the mean load, this feature affected high energy absorption capability. It is important to note that the vertex angle works as trigger mechanisms that prevent catastrophic failure of the composites result low energy absorption performance. Triggering mechanisms provide a progressive stable collapse through localized buckling.

CONCLUSIONS

The energy absorption characteristics are determined for conical composites using natural fibre (coir fibre), reinforced polyester composites. Conical composite contained different fibre volume fractions were compressed quasi-statically at constant cross-head displacement. The energy absorption capabilities and crushing modes were determined and as a function of fibre volume fractions and vertex angles. It was found that fibre loadings and vertex angles had played an important role in determining the energy absorption capabilities and crushing modes. An increase in vertex angle resulted in increasing specific energy absorptions and mean loads. Fibre loading greatly affected the specific energy absorption capability for each identical vertex angle. The 5^0 semi-vertex angles produced global buckling just after linear deformation during axial compressive loadings and the semi-vertex angle greater than 10^0 revealed stable progressive collapses that contributed to higher energy absorption performance.

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